Space Observation at Sofradir

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Jean-Pierre Chatard / Technical Director
Michel Vuillermet / Space Product Line Manager

SOFRADIR
43-47 rue Camille Pelletan
92290 Châtenay-Malabry / France

Jean-Paul Chamonal / Detector Technology Manager

CENG/LIR
17 rue des Martyrs
38054 Grenoble Cedex 9 / France

0. ABSTRACT

In the frame of space activities, Sofradir has developed a large know-how in the field of infrared detectors.

Thanks to some numbers of basic studies, thanks to its participation to the development and manufacturing of the Helios 2 program for which long linear arrays have been produced, Sofradir has established a Mercury Cadmium Telluride technology qualified for space applications.

Using MCT technology was a very good choice, not only for the level of performances but also for the flexibility of the material, as it is possible on the same base to manufacture SWIR, MWIR or LWIR detectors.

The purpose of the paper is to give some technical information and to present possible evolution of the detectors in regard of space observations.

1. INTRODUCTION

After several years of developing infrared detectors for the military tactical domain where quantities higher than 2000/year are now in production, Sofradir started to work in the field of space applications and especially in the earth observation domain.

Thanks to the work done with the support of the French Space Agency (Cnes), of the European Space Agency (Esa) and the French Ministry of Defence Sofradir has now a well-quality team of 15 people working on space programs.

In order to answer to the need of earth observations Sofradir propose the use of cooled and lightcooled Mercury Cadmium Telluride (HgCdTe/MCT) sensitive material which covers the spectral region from 1 µm to 14 µm [1] and the use of microbolometers which are sensitive in the long wave spectrum with the big advantage to be totally uncooled.

Thanks to these technologies developed by the French infrared research laboratory (Leti-Lir) and industrialised by Sofradir it has been possible to participate to key space technologies studies and to the largest military infrared program in Europe, Helios 2.

2. TECHNOLOGIES CAPABILITIES

2.1 Technology

The quality of the unique Mercury Cadmium Telluride (HgCdTe / MCT) process, which was transferred from CEA-LETI (LIR) in 1987, allows Sofradir to offer high performance IR detectors with respect to format and Electro Optical performance.

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Based on the new generation concept of infrared detectors (FPA), this technology assembled photovoltaic (PV) MCT diode arrays with complex readout silicon circuit (ROIC) which includes integration, gain and offset control, sampling, multiplexing and specific features. The assembly is done thanks to a special indium bump hybridization technique (figure 2.1).

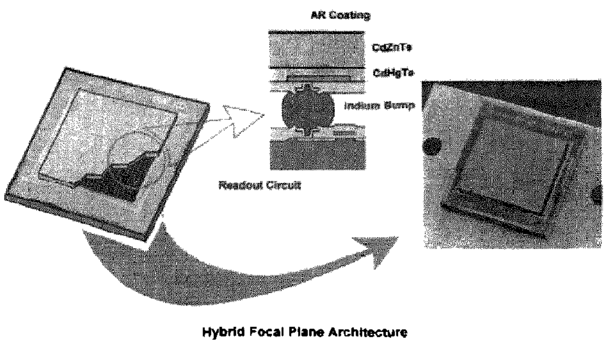


Figure 2.1 : dessin de la structure hybride

Sofradir technology key points are discussed in the following in order to highlight high performance technology parameters.

2.1.1 Wafer size

Sofradir substrates are issued from home-made Cadmium Zinc Telluride (CdZnTe) ingots sliced into crystal-oriented rectangular wafers. Since 1996, Sofradir has manufactured 60 mm (2.4") diameter CdZnTe ingots in which wafers are sliced.

Up to 1997, these wafers were standardized at 20 mm × 25 mm for the PV array manufacturing. Since 1998, the CdZnTe wafers have been increased to 36 mm × 38 mm at the production level, enabling larger detectors and/or more detectors per wafer (Figure 2.2).

This increase enabled for instance to step up the 2D array manufacturing from 30 μm pitch 320×256 arrays to 1 000x1 000 with 15 μm pitch.

The next step concerns processing of wafer size close to two inches diameter. This will be in production at Sofradir in 2001 for 2D staring arrays.

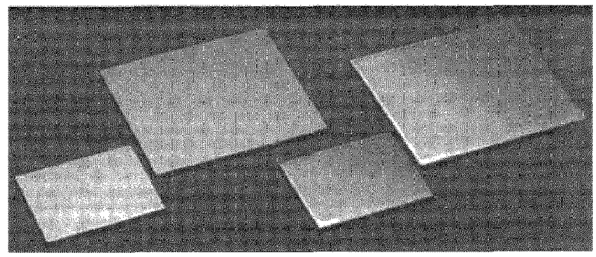


Figure 2.2: 20×25 mm² and 36×38 mm² PV wafers

(left : polished CdTe wafer ; right: with raw LPE grown detective HgCdTe layer)

2.1.2 HgCdTe process

On the detective process part, the Liquid Phase Epitaxy (LPE) growth of the HgCdTe layer has been the technological choice at Sofradir for more than 14 years. This process step is critical for the detection quality, spectral cut-off uniformity and reproducibility. It has been mastered and has demonstrated high yield and high reproducibility, making it the key point for the high performance detectors proposed by Sofradir.

Sofradir also investigates in cooperation with the CEA-LETI Infrared Laboratory (LIR) other technologies for detection array material manufacturing. The Molecular Beam Epitaxy (MBE) process on Germanium substrates is currently developed at LIR, for use on large arrays [2]. This enables even larger arrays than currently obtained with the LPE process, with a well mastered sensitive thin film thickness deposition.

2.1.3 Ion implantation process

Once the sensitive layer is grown and polished, the remaining step is to manufacture the photovoltaic (PV) diodes. The process chosen by Sofradir is the ion implantation process [3]. Unlike techniques like the diffusion process or the mesa structure process, the Sofradir ion implantation process enables the definition of sharp pixels with a planar technology (key point for an efficient passivation). The N on P homojunctions are implanted and provide a well controlled junction which combines with short diffusion lengths. This enables sharp diodes with high fill factor.

This is a Silicon-like planar technology which is now used at a large scale at Sofradir for more than 14 years.

2.1.4 Hybridization process

The Indium bump hybridization process at Sofradir is based on a unique reflow technique. This technique allows the HgCdTe array to be accurately and automatically self-aligned on its Silicon read-out circuit, and gives a perfect connection yield.

Moreover, it enables simultaneous multiple HgCdTe PV array hybridization on a single Silicon wafer [4], for producibility improvement and very large array manufacturing.

2.2 Specific means

2.2.1 Manufacturing means

General Sofradir front-end equipments are used to manufacture the retina. Some equipments were upgraded to work with some specific space application arrays.

In order to manufacture the space flight model in properly conditions of cleanness and confidentiality, all operations of assembly are performed in a dedicated clean room (figure 2.3).

Detector assembling is performed in class 100 areas with protection to avoid the electrostatic discharges.

This dedicated clean room is specially arranged with specific tools to operate very carefully on space products. Most of operations are performed with binocular vision and can be monitored by the customers in a meeting room with the help of a video system.

Pictures hereunder present main tools used for detector assembling. There are :

- visual control system (figure 2.4)
- gluing system for large arrays with very low defect of positioning between retina and package,
- automatic bond tool with a pull test (figure 2.5)
- optical three dimensional measurement system (figure 2.6)

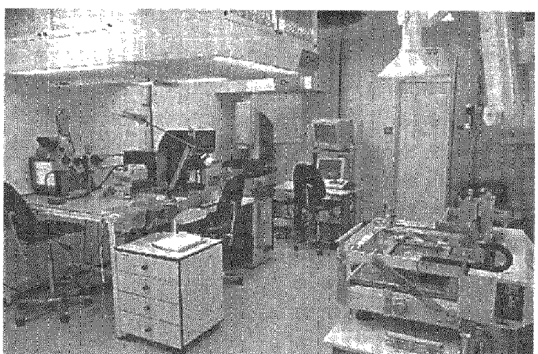


Figure 2.3 : Clean room overview

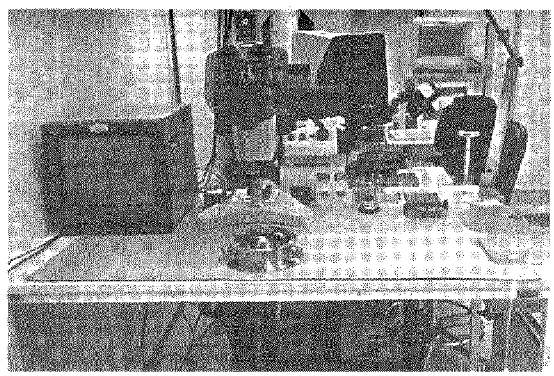


Figure 2.5 : Bonding tool

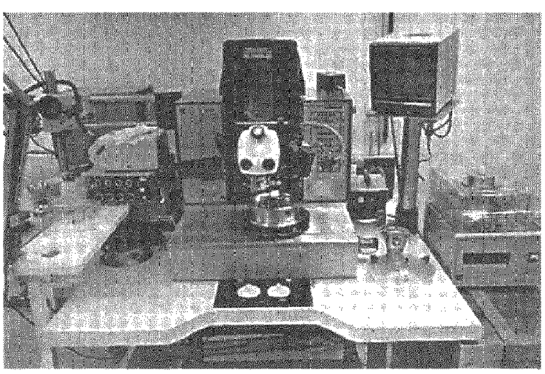


Figure 2.4 : Visual inspection station

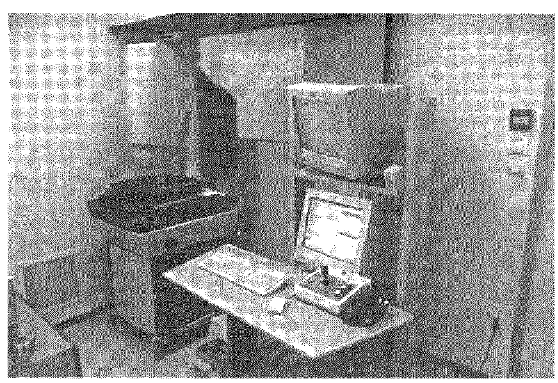


Figure 2.6 : Optical measurement system

2.2.2 Electrooptical test benches

The specific measurements performed to demonstrate the compliance with specification and the necessity to finely characterise the detector imposed the development of new test benches. Four electrooptical test benches were developed by Sofradir in less than two years.

It concerns :

- Radiometric
- Spectral
- Modulation Transfer Function
- Geometrical test benches.

Electronic system to operate detector and read the output signal was developed by Sofradir.

All test benches are regularly calibrated with a detector reference or other methods using specific detector of small dimension or material characteristics.

2.2.2.1 Radiometric test bench (figure 2.7)

The radiometric bench is specially designed to perform all measurements where controlled flux is necessary.

The main element of the bench is the blackbody confined into a vacuum chamber. The temperature control is better than 40 mK and the stability better than 3 mK peak to peak in the range -20°C / 60°C.

All optical parameters are controlled very carefully from the blackbody to the detector. For example, window temperature of the vacuum chamber and variation of blackbody emissivity, function of its temperature, are taken into account in the flux calculation. The bench is regularly controlled with an infrared reference detector.

The cryogenic system to cool down the detector developed under Sofradir specification allows a cold temperature stability of better than 5 mK peak to peak on the focal plane array.

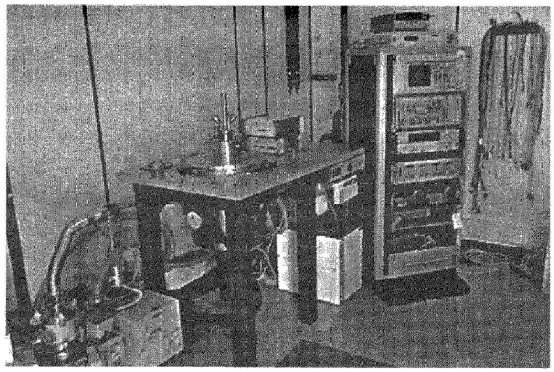


Figure 2.7 : Radiometric test bench

This test bench allows all radiometric measurement with very good conditions. For example, in case of Helios detector, linearity, signal to noise ration, 1/f noise up to 0.5 Hz and electrical characteristics are measured with this bench.

The accuracy of signal on noise ratio measurement is better than 2% in full range of blackbody temperature.

2.2.2.2 Spectral test bench (figure 2.8)

The spectral test bench is based on a Fourier transform spectrometer modified with Sofradir specifications.
This test bench allows to perform spectral response in the bandwidth 1 to 14 μm. Thanks to its principle, spectral measurement can be done on the same time on more than 200 diodes. Therefore, the spectral response of all diodes of an array can be measured within a reasonable duration.

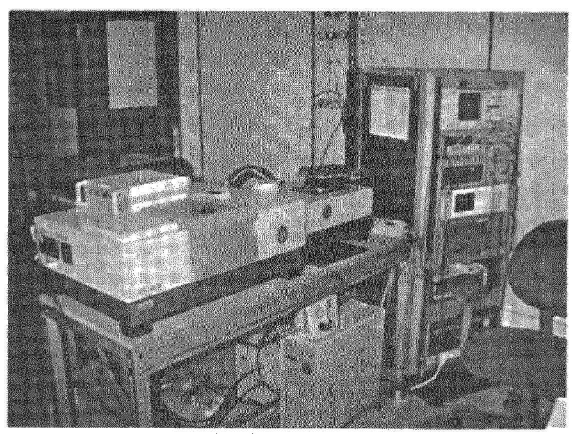


Figure 2.8 : Spectral test bench

2.2.2.3 Modulation transfer function test bench (figure 2.9)

The measurement of MTF is performed with the help of an edge shifted in front of the detector.

The detector MTF is calculated by Fourier transform of the detector response devised by the optical bench MTF. This last MTF is regularly measured with a small dimension detector (2 x 2 µm).

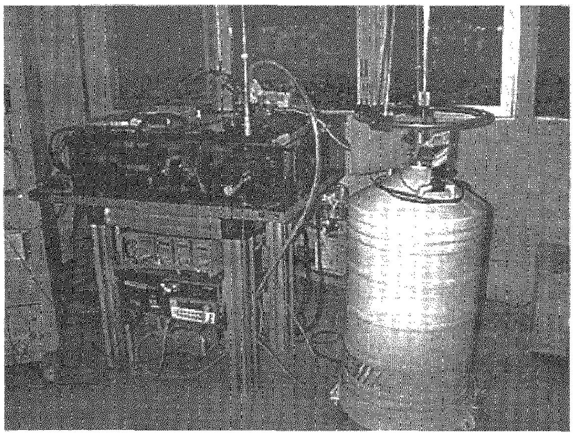


Figure 2.9 : MTF test bench

2.2.2.4 Geometrical test bench (figure 2.10)

This test bench was developed to measure the relative pixel position in the three axes.

For XY measurement the principle is to scan pixel lines from the first to the last pixel. The maximum of correlation function between two pixels response gives their relative position. Thanks to its high mechanical and optical control, the measurement accuracy is better than 0.5 µm from pixel to pixel and better than 5 µm all along the detector, up to 10 cm.

For Z measurement, the principle is to check by focalisation the maximum of pixel response. The method used allows an accuracy better than 2 µm. As a consequence, the flatness accuracy measurement is better than 4 µm.

Pixel spot scan, dynamic blooming and crosstalk measurements are possible with this bench.

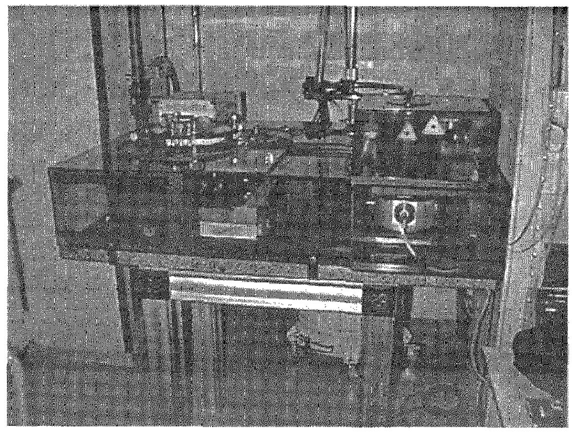


Figure 2.10 : Geometrical test bench

3. PROGRAMS

Different study programs have been done or are underway at Sofradir covering the spectral range from 1 µm to 14 µm using MCT material.

3.1 High Resolution Thermal Infrared Radiometric (HRTIR) [5] [6]

One of the most important Sofradir/Lir studies is certainly the HRTIR made in cooperation with Matra Marconi Space, Dasa and Officine Galileo under Esa support.

The principal aim of the HRTIR was to increase the understanding of energy, water and bioges chemical fluxes important in the study of land infrared processes. The HRTIR provides information on temperature and emissivity which is fundamental physical properties of terrestrial surfaces.

The detector works in the long wave region (8 to 12.5 µm) where the technology is always difficult to manage.

The product demonstrator was an assembly of two subarrays of 256 pixels each operating at 55 K (figure 3.1).

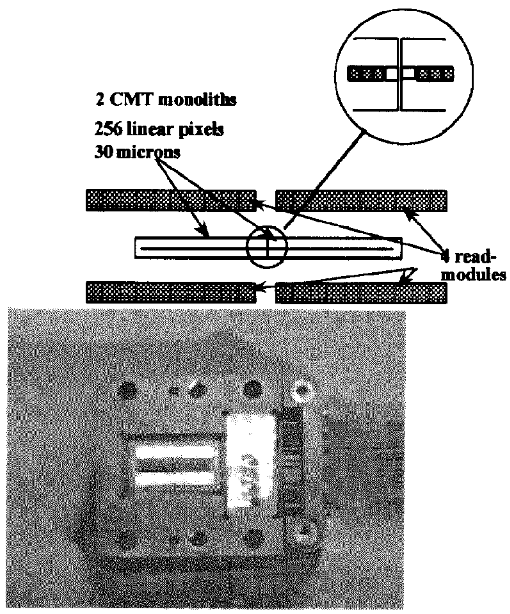


Figure 3.1 : LWIR HRTIR FPA breadboard

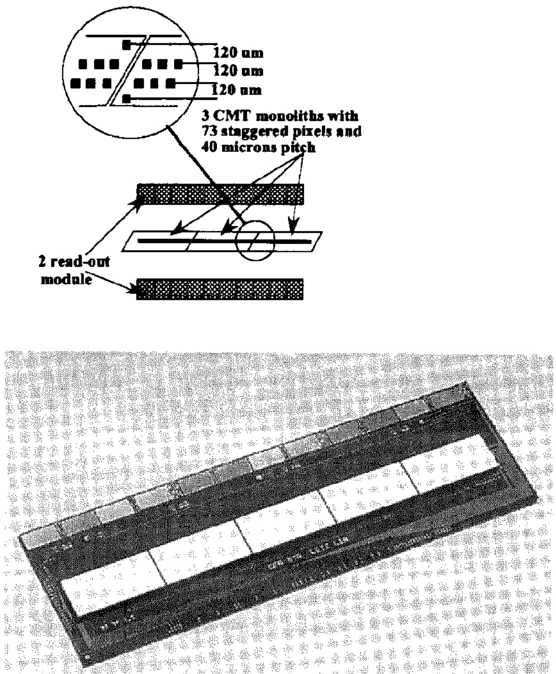


Figure 3.2 bis : 1500 x 1

Since that time Lir has demonstrated in the same spectral band an array of 1500 pixels by assembling 10 subarrays of 150 pixels (figure 3.2) with great success and no defect at the level of the buttings.

The technical objectives of the HRTIR detector breadboard manufacturing were to verify the performance of 12.5 μm cut off wavelength photodiodes operating at 50 K to assess the diodes operability and to check the self alignment of the subarrays.

The diode operability is a major issue for such thermal channels. Indeed, as the acquisition mode is based on the pushbroom principal, any defective pixel will lead to a dark column on the images.

The HRTIR detector breadboard shows that 97% of diodes are operational.

The dark currents (figure 3.3) are measured in a nearly zero background conditions when the FPA temperature can vary from 50 to 60 K. The mean dark current is 0.33 nA at 55 K (30 μm² pixels).

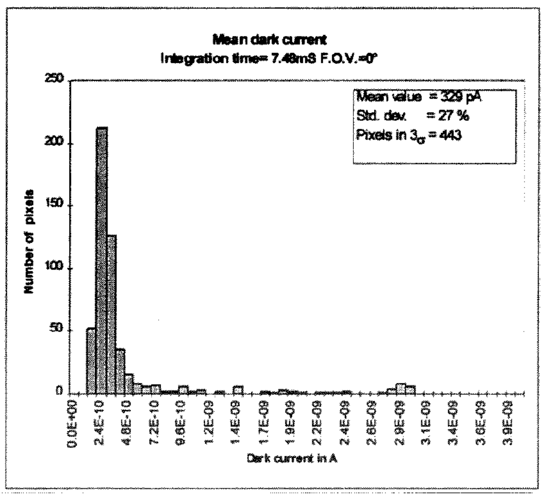


Figure 3.3 : Dark current distribution at 55 K

The dark signal uniformity defined by its standard deviation along the arrays is better than 27%. This figure can be improved a lot when the production phase will be considered. Figure 3.4 shows also the variation of the mean dark current versus the FPA temperature.

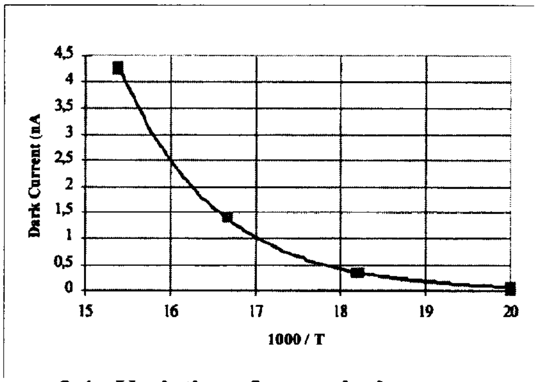
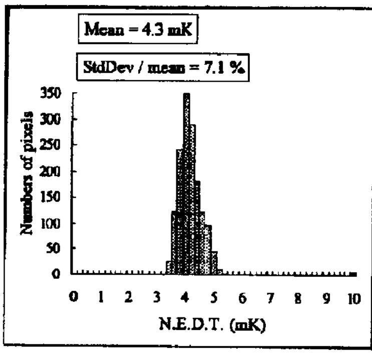
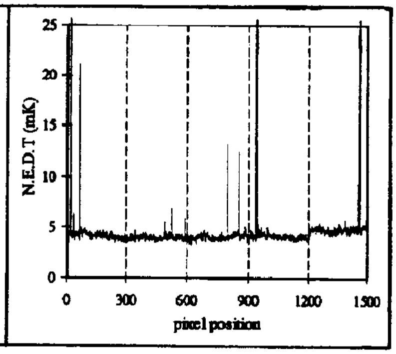


Figure 3.4 : Variation of mean dark current vs temperature in the 50-65 K range

Since the end of the HRTIR program the butting technology which allows to loose no pixel at the butting has been improved at Lir. Then bigger components have been demonstrated showing a very low number of defect [7] either in MW or LW spectral region (figure 3.2) (figure 3.5, figure 3.6) (figure 3.7, figure 3.8).

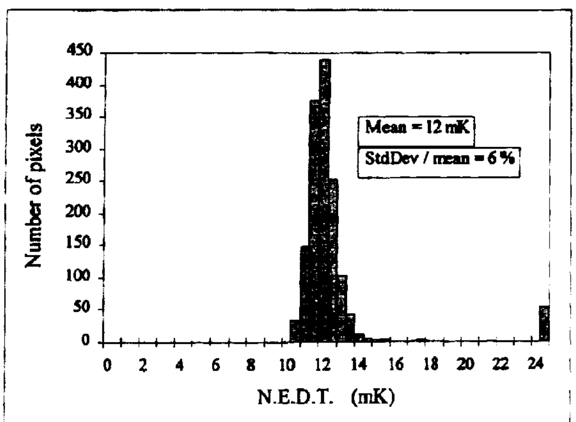




Operating temperature : 77 K
Field of view : 28°C
λc : 5.5 μm
Frame frequency : 200 Hz
Integration time : 5 ms

Figure 3.5 :
NEDT histogram

Figure 3.6 :
Spatial distribution of NEDT



NEDT histogram of the 1500 element linear LWIR butted array

Figure 3.7 : NEDT histogram of the 1500 element linear LWIR butted array

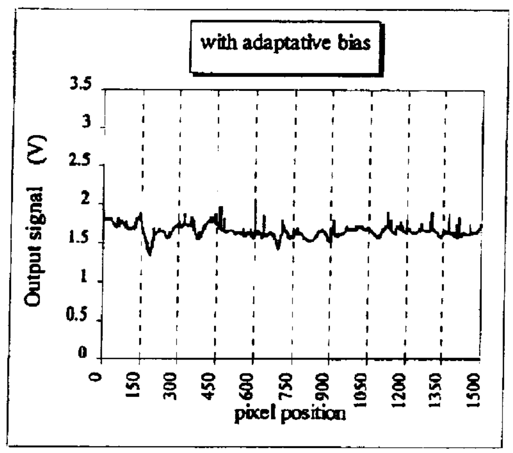
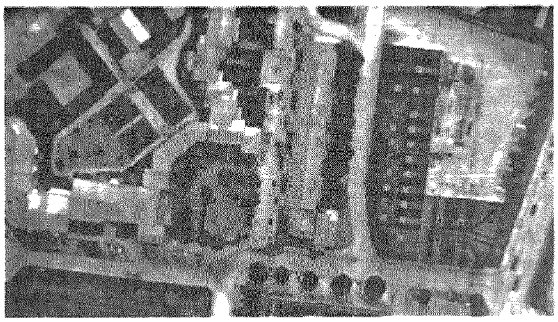


Figure 3.8 : Spatial distribution of NETD
Operating temperature : 78 mK
Field of view : 28°C
λc : 10 μm
Frame frequency : 150 Hz
Integration time : 2,4 ms

Earth observation (from helicopter) has been done by Onera and it is possible to compare different pictures taken at different wavelengths (figure 3.9).

Valence 3-5 µm (day time) :



Valence 8-10 µm (day time) :

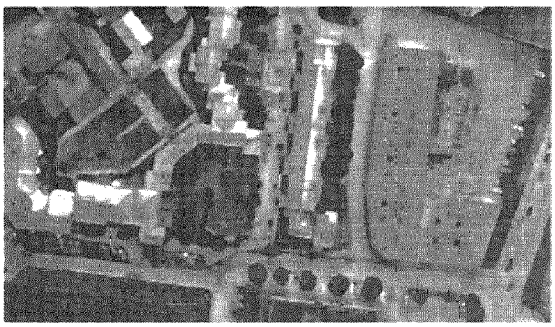


Figure 3.9 : Long linear MWIR and LWIR MCT detectors

3.2 Short wave infrared detector array for hyperspectral imagers

Sofradir starts the phase A of the Land Surface Processes and Interactive Missions (LSPIM) where a short wave large array is under development.

The large array of 256 rows of 1000 pixels with a pitch of 30 µm both directions is sensitive in the spectral bandwidth of 1 to 2.35 µm.

The program will be completed by end of 2001 with the delivery of prototypes.

This array will be a monolithic piece of HgCdTe hybridised to a ROIC. Whatever is the size of the array the standard technology will be used.

The selection of this approach is due to the good results obtained in the SWIR regions on diodes.

Figure 3.10 shows the prediction of the dark current versus FPA temperature and cut off wavelength as well as several experimental measurements which are in good accordance with the predicted figures.

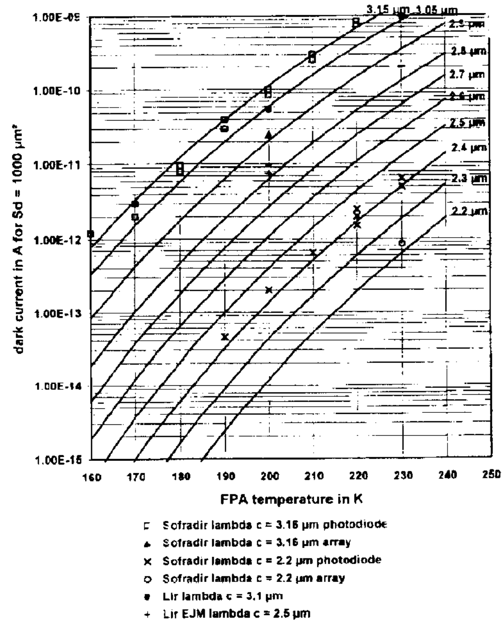


Figure 3.10 : dark current predictions

3.3 Large infrared linear array (Helios 2)

3.3.1 Summary of the development

The development of the infrared detector of Helios II (French military earth observation satellite) began in 1992 with the French Ministry of Defence. This development was based on the existing MCT and readout circuit technologies developed by the French Infrared Laboratory (LETI / LIR).

First, feasibility studies were supported by the Ministry of Defence. At the end of these studies the main choices concerning the detector, focal plane topology, infrared bandwidth, working temperature and number of pixels were done.

The detailed development began in 1994. Then, the direct customer was Alcatel Space Industries who is in charge of the detecting system. The first electrical breadboards was available at the end of 1995 to evaluate the main electrooptical and electrical performances.

The engineering model was delivered at the end of 1997.

Based on this detector, technology validation were made with success and the definitive design of the detector was presented in the middle of 1998.

The industrialisation and qualification models were available at the end of 1998 and the qualification test began in 1999.

Manufacturing of the flight model is in progress. The first flight model was delivered in June 2000. The second one and the extra model will be delivered this year.

3.3.2 Helios II detector characteristics

3.3.2.1 General characteristics

The Helios II detector is a large array of a large number of MCT photodiodes

MCT detecting modules and silicon readout circuit are hybridised by indium bumps onto an interconnection circuit.

The retina is integrated into a non hermetic packaging supporting filter, cold shield and thermal functions to control temperature and heat the detector for molecular decontamination. Two flex cables, one for retina functions and one for thermal functions, are implemented.

3.3.2.2 Electrooptical characteristics

3.3.2..2.1 Geometrical

System requirements concerning the geometrical characteristics of the detector are taken into account early in the detector development and were at the origin of lot of technological chooses.

Relative pixels location versus their theoretical locations is better than 1.0 µm along the detector. This high level of performance is insured by the technology used, hybridisation by indium bumps onto an interconnection circuit.

Low flatness of the detection array was one of the main parameters in the choice of the focal plane material. The challenge is to limit in the same time the thermo-mechanical deformation and the constraint in materials and assemblies.

In this case, thermo-mechanical deformation of the focal plane is less than 10 µm when the detector is cooled from the ambient to the cold temperature. This performance leads to a final detector flatness better than 20 µm at low temperature.

Absolute position of the detection line versus the mechanical interfaces is controlled by the assembling tools and is about +/- 50 µm.

3.3.2.2.2 Spectral (figure 3.11)

Spectral response is defined by a cold pass band filter located near the retina.

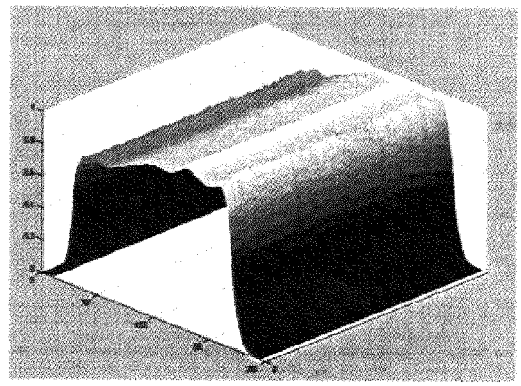


Figure 3.11 : Spectral response of all the diodes of the array

3.3.2.2.3 Radiometric

Low number of defects and high radiometric (signal / noise ratio) performances were required.

The high signal to noise ratio is mainly due to the high quantum efficiency and to the low noise level of MCT detectors. In term of noise, the readout circuit contribution is negligible and leads to a mean signal / noise ration very close to the theoretical limit.

The number of defects of a selected detector is very low. As an example the detector presented has zero defect. To obtain such performance, the detection modules were selected before hybridisation following their electrical characteristics measured on probe test bench and their visual aspect.

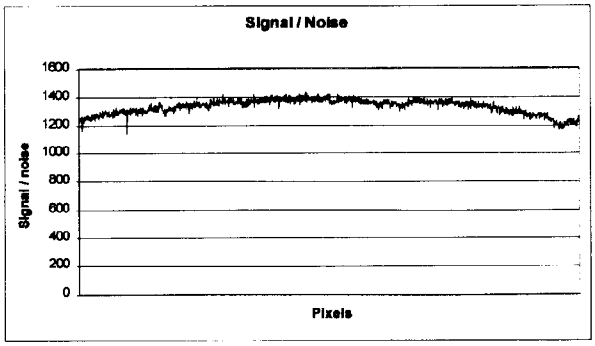


Figure 3.12

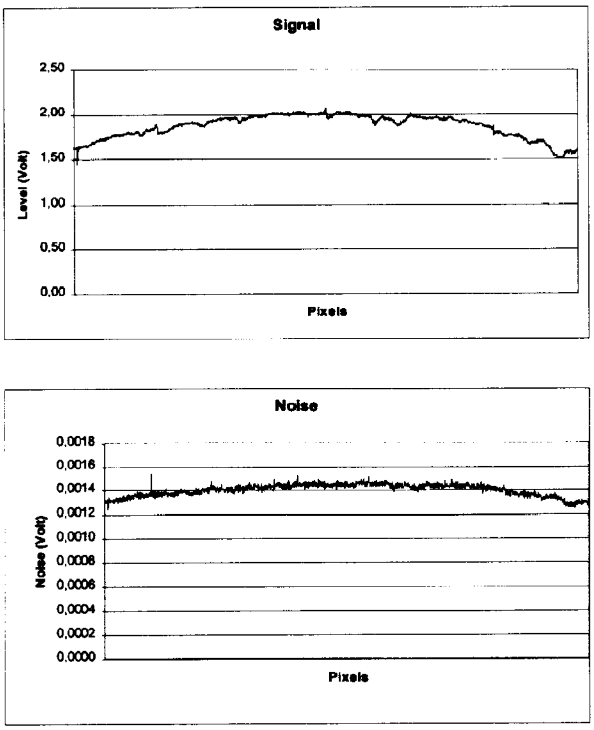


Figure 3.13

3.3.2.3 Environmental / Reliability

Detector reliability is better than 0.996 after 4 years of orbital life. This value was demonstrated based on Sofradir experience and specific tests.

For this detector, environmental characteristics before damage are :

Life time : ground life > 10 years
orbital life > 5 years

Working time > 5000 hours

Thermal cycles > 300
Radiation > 5 krad

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